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# **FUZZY LOGIC CONTROLLER FOR THE WHOLE BODY NMR IMAGING SYSTEM**

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## **1. INTRODUCTION**

Nuclear Magnetic Resonance Imaging (NMR Imaging) machines provide pictorial anatomical information about the physiological state of internal organs without the use of X- rays, and of all imaging methods, gives the most sensitive discrimination between healthy and diseased tissue. The resolution of whole body NMR imaging is limited by the accuracy and stability of the Field Gradient (FG) system. This paper considers the application of real-time fuzzy logic control to a field gradient system using a floating point digital signal processor (TMS320C40) to increase image resolution.

## **2. FIELD GRADIENT SYSTEM**

The important difference between NMR imaging and conventional NMR spectroscopy is the use of a field gradient system which allows the NMR effect across an area or volume to be mapped, and thus create an image. In summary, the FG system consists of three gradient coils for three mutually orthogonal field gradients and several power amplifiers with inner feedback loop. This inner feedback loop controls the amount of current which produces a magnetic field pattern in imaging space. The FG is affected by imperfections such as the geometrical deformations, skin effect, eddy currents effects, non-homogeneity in main magnet and RF coils, and magnetic effects of object to be imaged [1-8]. The relationship between coil current and FG is time-varying, non-linear and analytically intractable.

## **3. THE CONTROL PROBLEM**

Current NMR imaging systems employ an open-loop control strategy for the FG and assume that a fixed relationship exists between the coil current and FG. For a number of reasons such as geometrical changes and eddy current effects, there is an error between the desired and the actual magnetic field. The error introduces artefacts into the NMR image which effectively reduces the image resolution. It is therefore proposed to improve the NMR imaging system by measuring the gradients of field in three orthogonal direction and using it as a feedback signal in a closed-loop control system. The control problem in NMR imaging is to find an efficient strategy to compensate for the unknown and time varying dynamics of the field gradient system based on direct measurement of FG

## **4. FUZZY LOGIC CONTROL SYSTEM**

Fuzzy logic is a generalisation of classical logic to continuous logic [9,10]. There are two concepts within fuzzy logic which play a central role in its applications. The first one is a Linguistic variable, i.e. a variable whose values are words or sentences in a natural or synthetic language. This is the basis of fuzzy set theory which deals with the ambiguity found in semantics [11,12]. The second concept is that of a fuzzy IF-THEN rule in which the antecedent and consequent are propositions containing linguistic variables. This is the basis of the fuzzy measurement theory, which deals with the ambiguous nature of judgements and evaluations [13,14].

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These two concepts are effectively used in fuzzy logic controller for the FG system as illustrated in figure 1. After measuring the error (er) and change in error (δer) from the set point and field gradient sensors, their numerical values are fuzzified into linguistic values. A fuzzy inference engine judges and evaluates several linguistic values of control action by using fuzzy IF-THEN rules which are defined in principle base. Finally a fuzzified value of incremental control action (δu) is defuzzified into a crisp value which can be used to control the gradient of the magnetic field. Five fuzzy sets 'NB' ('Negative Big'), 'NS' ('Negative Small'), 'ZE' ('Zero'), 'PS' ('Positive Small') and 'PB' ('Positive Big') are defined for both input universe of discourse  $U = U_1 \times U_2 \subset \mathbb{R}^2$  and output universe of discourse  $V \subset \mathbb{R}$ . Fuzzy sets  $Er_n \subset U_1$ ,  $\Delta Er_n \subset U_2$  and  $\Delta u_n \subset V$  are fuzzy values of linguistic variable 'error', 'change in error'  $(er, \delta er)^T \in U$ , and 'incremental control action'  $\delta u \in V$  respectively, where  $n = 1, \dots, N$  and  $N$  is the number of fuzzy sets in each universe of discourse. Figure 2 shows the defined fuzzy sets. A body of knowledge about the plant is provided for the principle base in the form of;

$$R^{(m)}: \text{IF } er \text{ is } Er_n^m \text{ and IF } \delta er \text{ is } \Delta Er_n^m \text{ THEN } \delta u \text{ is } \Delta u_n^m \quad (1)$$

where  $m = 1, 2, \dots, M$  refers to rule number  $m$  and  $M$  is the number of rules in principle base. A set of rules ( $M=25$ ) in form of (1) are summarised in table 1. Based on fuzzy logic extension principle [15], the inference engine uses these rules to determine a mapping from fuzzy sets in the input universe of discourse  $U \subset \mathbb{R}^2$  to a fuzzy sets in the output universe of discourse  $V \subset \mathbb{R}$ . Each fuzzy IF-THEN rule in form of (1) defines a fuzzy set  $Er_n^m \times \Delta Er_n^m \rightarrow \Delta u_n^m$  in the product space  $U \times V$ . The membership functions of fuzzy sets in the output space can be calculated by triangular norms or so-called t-norm ( $\otimes$ ) and s-norms ( $\oplus$ ) for the intersection and union operations respectively. Let  $A'$  be an arbitrary input fuzzy set in  $U$ . According to different interpretations of fuzzy IF-THEN rule based on intuitive criteria or generalisation of classical logic, then a fuzzy set  $B^m$  in  $V$  can be written as  $B^m = A' \circ R^m$  or  $B^m = A' \bullet R^m$  where ' $\circ$ ' and ' $\bullet$ ' refer to s-t norm and t-s norm respectively. Then membership function of  $B^m$  can be either;

$$\mu_{A' \circ R^m}(\delta u) = \bigoplus_{(er, \delta er)^T \in U} [\mu_{A'}(er, \delta er) \otimes \mu_{Er_n^m \times \Delta Er_n^m \rightarrow \Delta u_n^m}(er, \delta er, \Delta u)] \quad (2)$$

or

$$\mu_{A' \bullet R^m}(\delta u) = \bigotimes_{(er, \delta er)^T \in U} [\mu_{A'}(er, \delta er) \oplus \mu_{Er_n^m \times \Delta Er_n^m \rightarrow \Delta u_n^m}(er, \delta er, \Delta u)] \quad (3)$$

The final output of the inference engine will be determined by considering the other  $M-1$  rules  $R^{(m)}$ . The result is a fuzzy set in  $V$  which is a combination of the  $M$  fuzzy sets  $A' \circ (R^{(1)}, \dots, R^{(M)})$ . The membership function of inferred fuzzy set will be;

$$\mu_{A' \circ (R^{(1)}, \dots, R^{(M)})}(\delta u) = \mu_{A' \circ R^{(1)}}(\delta u) \oplus \dots \oplus \mu_{A' \circ R^{(M)}}(\delta u) \quad (4)$$

The above membership function defines the fuzzy value of the control movement  $\mu_B(\delta u)$ . The crisp value of incremental control action can be obtained by using any defuzzification methods. Centre of gravity method is used here. In this method, the shape of membership function  $\mu_{A' \circ (R^{(1)}, \dots, R^{(M)})}(\delta u)$  is consider to determine the crisp control value by calculating the centre of gravity of the area bounded by the membership function curve, i.e.:

$$\delta u' = \frac{\int_{\mu} \delta u \mu_B(\delta u) d\delta u}{\int_{\mu} \mu_B(\delta u) d\delta u} \quad (5)$$

where  $\delta u'$  is the crisp value of incremental control action which can now be applied to the FG system of whole body NMR imaging. A control surface for measurements values of  $er'$ ,  $\delta er'$  and calculated numerical values of the incremental control action  $\delta u'$  is plotted as  $\delta u'$  versus  $er'$  and  $\delta er'$  shown in figure 3.

## 5. RESULTS

An IBM PC AT-bus plug-in QPC/C40B TMS320C4x parallel DSP system board of Loughborough Sound Images [16,17] has been programmed in C language to perform real-time computations and implementation. To attempt to meet the desired performance specifications such as tracking a reference signal with accuracy of 15 PPM and bandwidth of 20 kHz a separate analogue I/O board with 16-bit ADC/DAC and 200 kHz sampling rate are used to access the input/output analogue signals. Digital inputs are received through the DSPLINK2 parallel interface of the QPC/C40B. A PID controller is well tuned based on an approximated model of the FG system. Figure 4 shows an initial result of implementation of this PID controller to FG system. Fuzzy logic controller in this application is compiled as a high level programming language which allows a fast and more efficient implementation of digital control algorithm. The result of this compilation process for the closed-loop control of FG system is shown in figure 5.

## 6. CONCLUSION

The fuzzy logic controller in this application requires both numerical information that comes from sensors, and the linguistic description of control instructions which come from a human expert. It provides a systematic and efficient framework to compensate for non-linear, time varying and partly unknown dynamics of the field gradient system. Initial results indicate that the fuzzy logic controller will allow an appreciable increase in the speed of response and tracking of the reference signal when compared to a well tuned PID controller.

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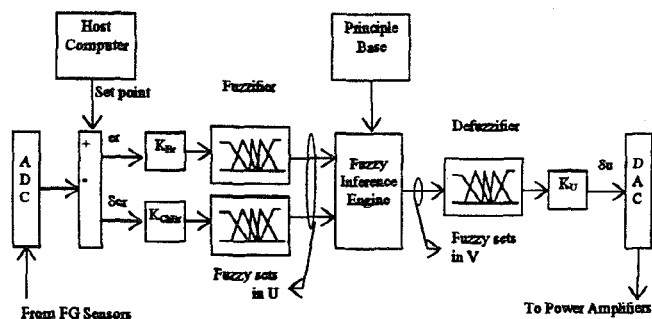


Figure 1, Block diagram of Interpreted Fuzzy logic controller for the whole body NMR imaging where implemented in an IBM PC AT-bus plug-in 50MHz TMS320C4x parallel DSP system with 16-bit ADC/DAC and 200 kHz sampling rate.

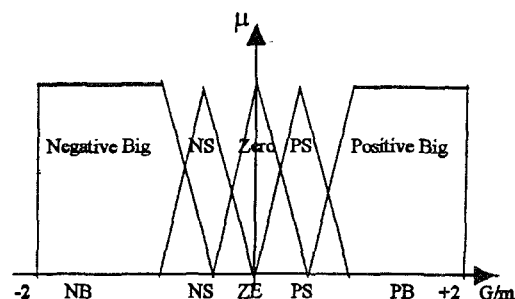


Figure 2, Partitioning the universe of discourse error, change in error and control movement into five fuzzy terms Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB).

error	Change In error				
	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NB	NB
NS	NB	NB	NS	NS	NS
ZE	NS	NS	ZE	PS	PS
PS	PS	PS	PS	PB	PB
PB	PB	PB	PB	PB	PB

Table 1, Principle Base for Field Gradient System.

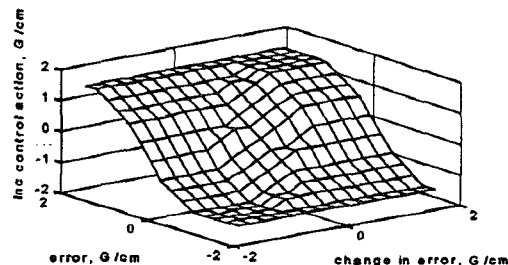


Figure 3, Fuzzy control surface which is resulted from the compiled fuzzy logic controller.

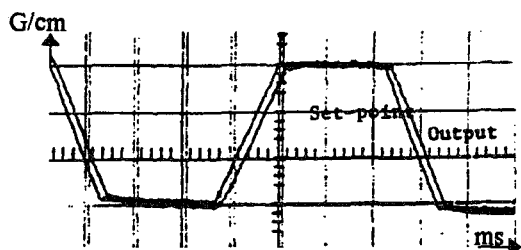


Figure 4, Result with a well tuned PID controller of the field gradient system.

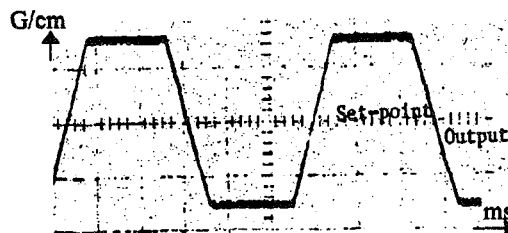


Figure 5, Result with fuzzy logic controller of the field gradient system.